Introduction:

This manuscript documents NREL's baseline wind turbine aeroelastic model for use in various offshore analysis concept studies. This includes the aeroelastic FAST[5] model, baseline control system (torque and pitch), and rationale behind the model. The turbine parameters are fictitious and do not represent an actual wind turbine, but do represent a good approximation of what an actual wind turbine of the associated size would be like.

The FAST model can be used to generate an ADAMS[7] model using the FAST-to-ADAMS preprocessor built-into FAST. NREL has compared the responses between the FAST and ADAMS model results for a number of simulations—the results agree pretty well in general—the most notable differences are caused by the availability of mass offsets and blade torsion DOFs in ADAMS, which are not available in FAST.

Numerous additional details and rationale may be found in the MS Excel workbook, NRELOffshrBsline5MW.xls, which is available from:

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General Machine Properties:

Before creating the aeroelastic model, the size/rating had to be settled on. It was understood from the onset that for a deepwater system to be cost-effective, each individual wind turbine must be rated at 5MW or higher. Ratings considered as the baseline included 5MW, 6MW, 7MW 10MW and up to 20MW. It was decided that the baseline should be 5MW since:

- Feasible floater configurations scoped out by NREL/NWTC were based on the assumption of a 5MW unit[13].
- Cost studies at DOE were based on a rotor diameter of 128m[13].
- 5MW has been used in a previous study, RECommendations for design of OFFshore wind turbines (RECOFF), from Europe[19].
- The largest wind turbine prototypes in the world, the Multibrid M5000[1,11,12] and REpower 5M[9,16,17], currently have ratings of 5MW.
- Machines, will likely get larger, not smaller.
- Thus, 5MW is an appropriate size and has a broad base of industry precedence.

Next, the aeroelastic properties of the 5MW baseline had to be established. In order for the concept studies to be defendable, the aeroelastic model had to be "realistic." In order to achieve "realism", NREL gathered publicly available gross properties of several aeroelastic models and created a composite from these systems, extracting the best available information. A summary of the aeroelastic models utilized is given below:

- FAST model of Global Energy Concept's (GEC's) Wind Partnerships for Advanced Component Development (WindPACT)[14] 5A02[10].
- FAST model of GEC's WindPACT 5A04[10].
- *BLADED* model used during Garrad Hassan's RECOFF project[19].
- *BLADED* and PHATAS models used during TU Delft's Dutch Offshore Wind Energy Converter (DOWEC) project[2,6,8].

and of the two largest wind turbine prototypes in the world:

- Multibrid M5000[1,11,12]
- REpower 5M[9,16,17]

These properties are provided in the following table:

Machine Data Comparisons of Several 5MW Wind Turbines and Models

Parameter	Units	Machine Data*					
Company	(-)	GEC	GEC	Garrad Hassan	TU Delft	Multibrid	REpower
Project	(-)	WindPACT 5A02	WindPACT 5A04	RECOFF	DOWEC	M5000	5M
Fictitious/Real	(-)	Fictitious	Fictitious	Fictitious	Fictitious	Real	Real
IEC Class	(-)	1A	2A		1C	1A	
Rated Power	MW	5.000	5.000	5.000	6.000	5.000	5.000
Number of Blades	(-)	3	3	3	3	3	3
Rated Wind Speed	m/s				12.000	12.000	13.000
Diameter	m	120.000	128.000	118.000	129.000	116.000	126.000
Blade Length	m	57.000	60.800	57.000	62.700		61.500
Hub Diameter	m	6.000	6.400	4.000	3.600		3.000
Hub Height	m	100.000	100.000	80.000	91.400	85.000	90.000-100.000
Gearbox Ratio	(-)	174.000	160.850	86.390	92.873	99.234	97.000
Rated Generator Speed	rpm	1,800.000	1,800.000	1,200.000	1,100.000	1,468.663	1,173.700
Rated Rotor Speed	rpm	10.345	11.191	13.890	11.844	14.800	12.100
Rated Tip Speed	m/s	64.998	75.000	85.822	80.000	89.891	79.828
Overhang	m	6.000	6.000	6.000	5.000		
Blade Precone	deg	0.000	0.000	0.000	2.500	2.000	> 0
Shaft Tilt	deg	5.000	5.000	4.000	5.000	5.000	> 0
Blade Mass	kg	21,170.000	27,812.000	13,813.000	17,905.000	16,500.000	17,740.000
Blade Second Mass Moment	kg*m^2	11,078,654.000		8,004,681.000	11,676,630.000		
Hub Mass	kg	109,345.000	125,970.000	50,000.000	30,000.000	58,200.000	56,780.000
Hub Inertia	kg*m^2	711,411.000	935,700.000	110,000.000	50,700.000		
Rotor Mass	kg	172,855.000	209,406.000	91,439.000	83,715.000	107,700.000	110,000.000
Rotor Inertia	kg*m^2	41,676,612.000		27,392,980.000	39,047,480.000		
Nacelle Mass	kg	246,626.000	270,669.000	250,000.000	187,952.000	194,090.000	240,000.000
Nacelle Yaw Inertia	kg*m^2	816,681.000		0.000	2,420,000.000		
Tower Top Mass	kg	419,481.000	480,075.000	341,439.000	271,667.000	301,790.000	350,000.000
Tower Mass	kg	499,635.000	503,000.000	540,294.500	345,370.600		
Total Mass of Turbine	kg	919,116.000	983,075.000	881,733.500	617,037.600		
Maximum Chord	m	5.295	5.120	4.440	4.620		4.600
Maximum Twist	deg	11.100	11.100	13.000	13.500		

*Values highlighted in green are the closest match to REpower 5M
*Values highlighted in red are untuned estimates

Note that the rotor diameters supplied in the table above ignore the effects of blade precone, which reduce the actual rotor diameter and swept area.

The Multibrid M5000 machine has a significantly higher tip speed than typical onshore wind turbines and lower tower top mass than would be expected from recently developed scaling laws[18]. In contrast, the REpower 5M machine has properties that are more "expected." In this sense, the REpower 5M machine is more "conventional" than the Multibrid M5000, so it makes sense to use the specifications of the REpower 5M machine as the target specifications for the model. Thus the task was to establish an aeroelastic model that tries to resemble the REpower 5M machine as close as possible (i.e., as close as publicly known) and to fill in the data "gaps" using machine properties known from the DOWEC, RECOFF, and WindPACT studies. From the table above, the DOWEC turbine most closely matched the REpower 5M machine, which makes sense since the DOWEC study used aeroelastic blade properties provided by LM glasfiber[9], and the REpower 5M machine also utilizes LM glasfiber blades. As such, must of the data "gaps" are filled in using machine properties from the DOWEC study[6].

Knowing that the rotor radius for our aeroelastic model would be about 63m (from the REpower 5M machine), and wanting the lowest reasonable hub-height possible in order to minimize the overturning moment of the platform, NREL decided that the hub height for the baseline model should be 90m, which would give a 15m air gap between the blade tips at their lowest point and a 30m (15m amplitude) 50-yr extreme wave height.

Additional gross properties chosen for the NREL 5MW baseline wind turbine, most of which are identical to the REpower 5M, are provided in the table below:

Gross Properties Chosen for the NREL 5MW Baseline Wind Turbine Model

Rating	5MW	
Wind Regime	IEC 61400-3 (Offshore) Class 1B / Class 6 winds	
Rotor Orientation	Upwind	
Control	Variable Speed, Collective Pitch	
Rotor Diameter / Hub Diameter	126m / 3m	
Hub Height	90m	
Maximum Rotor / Generator Speed	12.1rpm / 1,173.7rpm	
Maximum Tip Speed	80m/s	
Overhang / Shaft Tilt / Precone	5m / 5º / 2.5º	
Rotor Mass	110,000kg	Overall c.g. location:
Nacelle Mass	240,000kg	(x_t,y_t,z_t) = (-0.2m,0.0m,64.0m)
Tower Mass (Deepwater)	347,460kg	
Reference Site	National Data Buoy Center (NDBC) Buoy 44008	

The tower mass listed in the table above is for the deepwater support structure configuration. The overall c.g. location of this wind turbine as indicated above is in the tower base coordinate system whose origin lies on the tower centerline at the mean sea level (MSL).

The aeroelastic FAST model, which can't support prebend, incorporates a 2.5º upwind precone. This is used to represent the small amount of precone and larger amount of precurve built-into the actual REpower 5M, 61.5m long, LM glasfiber blade[9]. The rotor and hub diameters indicated in the table above ignore the effects of blade precone, which reduces the actual diameters and swept area. The actual rotor diameter in the model (assuming that the blades are undeflected) is (126m)*COS(2.5º) = 125.88m and the actual swept area is (π/4)*(125.88m)^2 = 12,445.3m^2.

Blade Structural Properties:

The distributed blade structural properties of the NREL 5MW baseline model are based on the structural properties of the 62.6m long LM Glasfiber blade used in the DOWEC study, as given in Appendix A of Ref. 8. Since the blades in the DOWEC study are 1.1m longer than the REpower 5M blades, the structural properties of the NREL 5MW baseline blade are found by truncating the 62.6m blades at 61.5m blade span (the structural properties of the blade tip are found by interpolating between the 61.2m and 61.7m stations provided in Appendix A of Ref. 8). The resulting properties are given in the table below:

Distributed Blade Structural Properties

Radius (m)	BlFract (-)	AeroCent (-)	StrcTwst (deg)	BMassDen (kg/m)	FlpStff (Nm^2)	EdgStff (Nm^2)	GJStff (Nm^2)	EAStff (N)	Alpha (-)	FlpIner (kg m)	EdgIner (kg m)	PrecrvRef (m)	PreswpRef (m)	FlpcgOf (m)	EdgcgOf (m)
1.50	0.00000	0.25000	13.308	678.935	18110.00E+6	18113.60E+6	5564.40E+6	9729.48E+6	0.0	972.86	973.04	0.0	0.0	0.0	0.00017
1.70	0.00325	0.25000	13.308	678.935	18110.00E+6	18113.60E+6	5564.40E+6	9729.48E+6	0.0	972.86	973.04	0.0	0.0	0.0	0.00017
2.70	0.01951	0.24951	13.308	773.363	19424.90E+6	19558.60E+6	5431.59E+6	10789.50E+6	0.0	1091.52	1066.38	0.0	0.0	0.0	-0.02309
3.70	0.03577	0.24510	13.308	740.550	17455.90E+6	19497.80E+6	4993.98E+6	10067.23E+6	0.0	966.09	1047.36	0.0	0.0	0.0	0.00344
4.70	0.05203	0.23284	13.308	740.042	15287.40E+6	19788.80E+6	4666.59E+6	9867.78E+6	0.0	873.81	1099.75	0.0	0.0	0.0	0.04345
5.70	0.06829	0.22059	13.308	592.496	10782.40E+6	14858.50E+6	3474.71E+6	7607.86E+6	0.0	648.55	873.02	0.0	0.0	0.0	0.05893
6.70	0.08455	0.20833	13.308	450.275	7229.72E+6	10220.60E+6	2323.54E+6	5491.26E+6	0.0	456.76	641.49	0.0	0.0	0.0	0.06494
7.70	0.10081	0.19608	13.308	424.054	6309.54E+6	9144.70E+6	1907.87E+6	4971.30E+6	0.0	400.53	593.73	0.0	0.0	0.0	0.07718
8.70	0.11707	0.18382	13.308	400.638	5528.36E+6	8063.16E+6	1570.36E+6	4493.95E+6	0.0	351.61	547.18	0.0	0.0	0.0	0.08394
9.70	0.13335	0.17156	13.308	382.062	4980.06E+6	6884.44E+6	1158.26E+6	4034.80E+6	0.0	316.12	490.84	0.0	0.0	0.0	0.10174
10.70	0.14959	0.15931	13.308	399.655	4936.84E+6	7009.18E+6	1002.12E+6	4037.29E+6	0.0	303.60	503.86	0.0	0.0	0.0	0.10758
11.70	0.16585	0.14706	13.308	426.321	4691.66E+6	7167.68E+6	855.90E+6	4169.72E+6	0.0	289.24	544.70	0.0	0.0	0.0	0.15829
12.70	0.18211	0.13481	13.181	416.820	3949.46E+6	7271.66E+6	672.27E+6	4082.35E+6	0.0	246.57	569.90	0.0	0.0	0.0	0.22235
13.70	0.19837	0.12500	12.848	406.186	3386.52E+6	7081.70E+6	547.49E+6	4085.97E+6	0.0	215.91	601.28	0.0	0.0	0.0	0.30756
14.70	0.21465	0.12500	12.192	381.420	2933.74E+6	6244.53E+6	448.84E+6	3668.34E+6	0.0	187.11	546.56	0.0	0.0	0.0	0.30386
15.70	0.23089	0.12500	11.561	352.822	2568.96E+6	5048.96E+6	335.92E+6	3147.76E+6	0.0	160.84	468.71	0.0	0.0	0.0	0.26519
16.70	0.24715	0.12500	11.072	349.477	2388.65E+6	4948.49E+6	311.35E+6	3011.58E+6	0.0	148.56	453.76	0.0	0.0	0.0	0.25941
17.70	0.26341	0.12500	10.792	346.538	2271.99E+6	4808.02E+6	291.94E+6	2882.62E+6	0.0	140.30	436.22	0.0	0.0	0.0	0.25007
19.70	0.29595	0.12500	10.232	339.333	2050.05E+6	4501.40E+6	261.00E+6	2613.97E+6	0.0	124.61	398.18	0.0	0.0	0.0	0.23155
21.70	0.32846	0.12500	9.672	330.004	1828.25E+6	4244.07E+6	228.82E+6	2357.48E+6	0.0	109.42	362.08	0.0	0.0	0.0	0.20382
23.70	0.36098	0.12500	9.110	321.990	1588.71E+6	3995.28E+6	200.75E+6	2146.86E+6	0.0	94.36	335.01	0.0	0.0	0.0	0.19934
25.70	0.39350	0.12500	8.534	313.820	1361.93E+6	3750.76E+6	174.38E+6	1944.09E+6	0.0	80.24	308.57	0.0	0.0	0.0	0.19323
27.70	0.42602	0.12500	7.932	294.734	1102.38E+6	3447.14E+6	144.47E+6	1632.70E+6	0.0	62.67	263.87	0.0	0.0	0.0	0.14994
29.70	0.45855	0.12500	7.321	287.120	875.80E+6	3139.07E+6	119.98E+6	1432.40E+6	0.0	49.42	237.06	0.0	0.0	0.0	0.15421
31.70	0.49106	0.12500	6.711	263.343	681.30E+6	2734.24E+6	81.19E+6	1168.76E+6	0.0	37.34	196.41	0.0	0.0	0.0	0.13252
33.70	0.52358	0.12500	6.122	253.207	534.72E+6	2554.87E+6	69.09E+6	1047.43E+6	0.0	29.14	180.34	0.0	0.0	0.0	0.13313
35.70	0.55610	0.12500	5.546	241.666	408.90E+6	2334.03E+6	57.45E+6	922.95E+6	0.0	22.16	162.43	0.0	0.0	0.0	0.14035
37.70	0.58862	0.12500	4.971	220.638	314.54E+6	1828.73E+6	45.92E+6	760.82E+6	0.0	17.33	134.83	0.0	0.0	0.0	0.13950
39.70	0.62115	0.12500	4.401	200.293	238.63E+6	1584.10E+6	35.98E+6	648.03E+6	0.0	13.30	116.30	0.0	0.0	0.0	0.15134
41.70	0.65366	0.12500	3.834	179.404	175.88E+6	1323.36E+6	27.44E+6	539.70E+6	0.0	9.96	97.98	0.0	0.0	0.0	0.17418
43.70	0.68618	0.12500	3.332	165.094	126.01E+6	1183.68E+6	20.90E+6	531.15E+6	0.0	7.30	98.93	0.0	0.0	0.0	0.24922
45.70	0.71870	0.12500	2.890	154.411	107.26E+6	1020.16E+6	18.54E+6	460.01E+6	0.0	6.22	85.78	0.0	0.0	0.0	0.26022
47.70	0.75122	0.12500	2.503	138.935	90.88E+6	797.81E+6	16.28E+6	375.75E+6	0.0	5.19	69.96	0.0	0.0	0.0	0.22554
49.70	0.78376	0.12500	2.116	129.555	76.31E+6	709.61E+6	14.53E+6	328.89E+6	0.0	4.36	61.41	0.0	0.0	0.0	0.22795
51.70	0.81626	0.12500	1.730	107.264	61.05E+6	518.19E+6	9.07E+6	244.04E+6	0.0	3.36	45.44	0.0	0.0	0.0	0.20600
53.70	0.84878	0.12500	1.342	98.776	49.48E+6	454.87E+6	8.06E+6	211.60E+6	0.0	2.75	39.57	0.0	0.0	0.0	0.21662
55.70	0.88130	0.12500	0.954	90.248	39.36E+6	395.12E+6	7.08E+6	181.52E+6	0.0	2.21	34.09	0.0	0.0	0.0	0.22784
56.70	0.89756	0.12500	0.760	83.001	34.67E+6	353.72E+6	6.09E+6	160.25E+6	0.0	1.93	30.12	0.0	0.0	0.0	0.23124
57.70	0.91382	0.12500	0.574	72.906	30.41E+6	304.73E+6	5.75E+6	109.23E+6	0.0	1.69	20.15	0.0	0.0	0.0	0.14826
58.70	0.93008	0.12500	0.404	68.772	26.52E+6	281.42E+6	5.33E+6	100.08E+6	0.0	1.49	18.53	0.0	0.0	0.0	0.15346
59.20	0.93821	0.12500	0.319	66.264	23.84E+6	261.71E+6	4.94E+6	92.24E+6	0.0	1.34	17.11	0.0	0.0	0.0	0.15382
59.70	0.94636	0.12500	0.253	59.340	19.63E+6	158.81E+6	4.24E+6	63.23E+6	0.0	1.10	11.55	0.0	0.0	0.0	0.09470
60.20	0.95447	0.12500	0.216	55.914	16.00E+6	137.88E+6	3.66E+6	53.32E+6	0.0	0.89	9.77	0.0	0.0	0.0	0.09018
60.70	0.96260	0.12500	0.178	52.484	12.83E+6	118.79E+6	3.13E+6	44.53E+6	0.0	0.71	8.19	0.0	0.0	0.0	0.08561
61.20	0.97073	0.12500	0.140	49.114	10.08E+6	101.63E+6	2.64E+6	36.90E+6	0.0	0.56	6.82	0.0	0.0	0.0	0.08035
61.70	0.97886	0.12500	0.101	45.818	7.55E+6	85.07E+6	2.17E+6	29.92E+6	0.0	0.42	5.57	0.0	0.0	0.0	0.07096
62.20	0.98699	0.12500	0.062	41.669	4.60E+6	64.26E+6	1.58E+6	21.31E+6	0.0	0.25	4.01	0.0	0.0	0.0	0.05424
62.70	0.99512	0.12500	0.023	11.453	0.25E+6	6.61E+6	0.25E+6	4.85E+6	0.0	0.04	0.94	0.0	0.0	0.0	0.05387
63.00	1.00000	0.12500	0.000	10.319	0.17E+6	5.01E+6	0.19E+6	3.53E+6	0.0	0.02	0.68	0.0	0.0	0.0	0.05181

The entries in the first column, Radius, are the spanwise locations along the blade pitch axis relative to the rotor center (apex).

BlFract is the fractional distance along the blade pitch axis from the root (0.0) to the tip (1.0). The blade root is located 1.5m along the pitch axis from the rotor center (apex).

AeroCent is a FAST variable name. FAST assumes that the pitch axis passes through the each airfoil section at 25% chord. By definition, the quantity (AeroCent - 0.25) is the fractional distance to the aerodynamic center from the pitch axis along the chordline, positive towards the trailing edge. Thus, at the root (BlFract = 0.0), AeroCent = 0.25 means that the aerodynamic center lies on the pitch axis [since (0.25 - 0.25) = 0.0]. And at the tip (BlFract = 1.0), AeroCent

= 0.125 means that the aerodynamic center lies 0.125 chordlengths toward the leading edge from pitch axis [since (0.125 - 0.25) = -0.125].

The flapwise and edgwise section stiffness and inertia values, FlpStff, EdgStff, FlpIner and EdgIner, are given about the principal structural axes of each cross section as oriented by the structural twist angle, StrcTwst. The values of StrcTwst as given in the table above, are offset by -0.09182º from the values provided in Appendix A of Ref. 8 in order to insure that the zero-twist reference location is at the blade tip.

GJStff are the values of the blade torsional stiffness. Since the DOWEC blade data did not contain extensional stiffness information, the blade extensional stiffness values, EAStff, given in the table above were estimated to be 10^7 times the average mass moment of inertia at each blade station (this rule of thumb comes from WindPACT data). This rule of thumb should get us in the ballpark at least—the exact values are not important due to the low rotational speed.

The flapwise c.g. offset values, FlpcgOf, and flapwise and edgewise elastic offset values, FlpEAOf and EdgEAOf, given in the table above were assumed to be zero due to the inability to decipher the corresponding information given in Appendix A of Ref. 8. The edgewise c.g. offset values, EdgcgOf, are the distances in meters along the chordline from the pitch axis to the center of gravity of the blade section, positive towards the trailing edge.

The distributed blade section mass per unit length values, BMassDen, given in the table above are increased by 4.536% in the model in order to scale the overall (integrated) blade mass to 17,740kg, which is the mass of the blades in the REpower 5M machine. In the model, the second mass moment of inertia, first mass moment of inertia, and the radial c.g. location of each blade is 11,776,047 kg-m^2, 363,231 kg-m, and 20.475m with respect to the blade root, respectively.

The NREL 5MW baseline model incorporates 0.477465% critical structural damping in all modes of the isolated blade, which corresponds to the 3% logarithmic decrement used in the DOWEC study from page 20 of Ref. 6.

The table below summarizes the undistributed blade structural properties discussed in this section:

Undistributed Blade Structural Properties

Length (w.r.t. Root Along Preconed Axis)	61.5 m
Mass Scaling Factor	4.536 %
Overall (Integrated) Mass	17,740 kg
Second Mass Moment of Inertia (w.r.t. Root)	11,776,047 kg-m^2
First Mass Moment of Inertia (w.r.t. Root)	363,231 kg-m
c.g. Location (w.r.t. Root Along Preconed Axis)	20.475 m
Structural Damping Ratio (All Modes)	0.477465 %

Blade Aerodynamic Properties:

Like the blade structural properties, the blade aerodynamic properties are also based on the DOWEC blade as described in Table 1 on page 13 of Ref. 6 and Appendix A of Ref. 8. The model uses 17 blade elements for integration of the aerodynamic and structural forces. The inboard 3 and outboard 3 elements are two-thirds the size of the 11 equally-spaced midspan elements in order to better capture the large structural gradients at the blade root and the large aerodynamic gradients at the blade tip. The aerodynamic properties at the blade nodes, which are located at the center of the blade elements, are given in the table below. The blade node locations, labeled as RNodes in the table, are directed along the pitch axis from the rotor center (apex) to the blade cross sections.

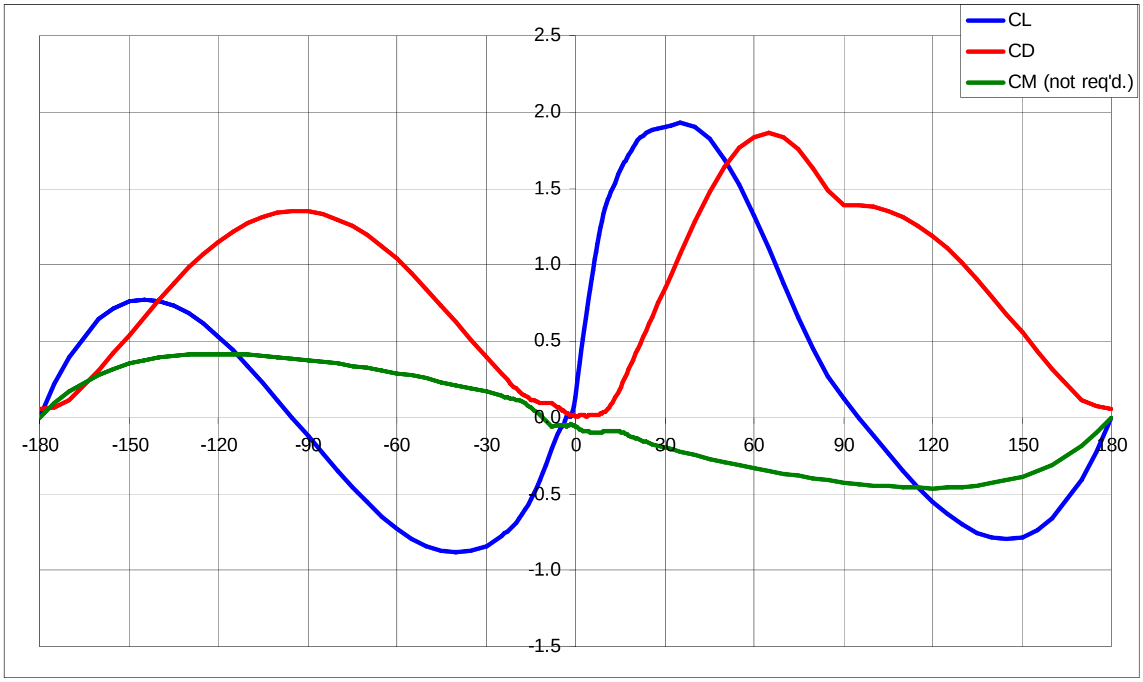
Distributed Blade Aerodynamic Properties

Node (-)	RNodes (m)	AeroTwst (deg)	DRNodes (m)	Chord (m)	Airfoil Table (-)
1	2.8667	13.308	2.7333	3.542	Cylinder1.dat
2	5.6000	13.308	2.7333	3.854	Cylinder1.dat
3	8.3333	13.308	2.7333	4.167	Cylinder2.dat
4	11.7500	13.308	4.1000	4.557	DU40_A17.dat
5	15.8500	11.480	4.1000	4.652	DU35_A17.dat
6	19.9500	10.162	4.1000	4.458	DU35_A17.dat
7	24.0500	9.011	4.1000	4.249	DU30_A17.dat
8	28.1500	7.795	4.1000	4.007	DU25_A17.dat
9	32.2500	6.544	4.1000	3.748	DU25_A17.dat
10	36.3500	5.361	4.1000	3.502	DU21_A17.dat
11	40.4500	4.188	4.1000	3.256	DU21_A17.dat
12	44.5500	3.125	4.1000	3.010	NA64_A17.dat
13	48.6500	2.319	4.1000	2.764	NA64_A17.dat
14	52.7500	1.526	4.1000	2.518	NA64_A17.dat
15	56.1667	0.863	2.7333	2.313	NA64_A17.dat
16	58.9000	0.370	2.7333	2.086	NA64_A17.dat
17	61.6333	0.106	2.7333	1.419	NA64_A17.dat

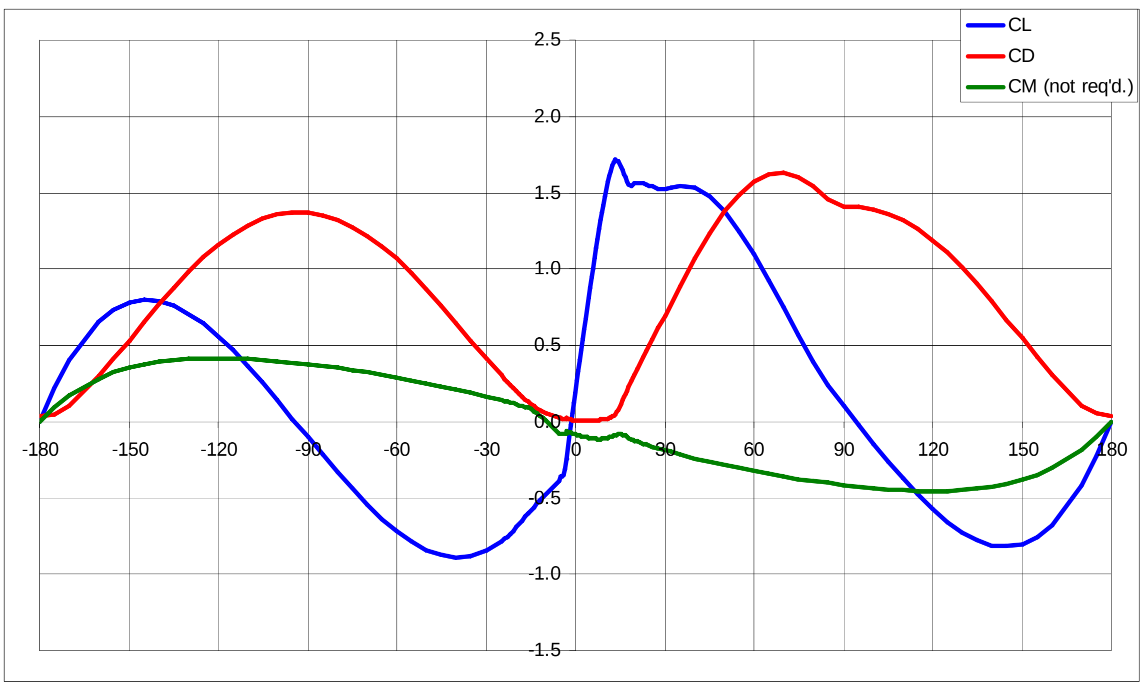
Integrating the chord distribution along the blade span reveals that the rotor solidity is roughly 5.16%.

As indicated in the table above, the NREL 5MW baseline model incorporates eight unique airfoil data tables. The two innermost airfoil tables represent cylinders with drag coefficients of 0.50 (Cylinder1.dat) and 0.35 (Cylinder2.dat) and no lift. The remaining six airfoil tables were created by incorporating 3D corrections to the 2D airfoil data coefficients of the six airfoils used in the DOWEC study as detailed in Appendix A of Ref. 6 (numerical values for these coefficients were provided by Koert Lindenburg of ECN). The lift (Cl) and drag (Cd) values were corrected for rotational stall delay for 0 to 90deg angle-of-attack, the Cd values were additionally corrected using the Viterna method for 0 to 90deg angle-of-attack, and the Beddoes-Leishman stall hysteresis parameters were found using version 2.0 of AirfoilPrep[3]. All corrections were made assuming an aspect ratio of 17. The 3D corrected airfoil data coefficients are illustrated graphically in the figures below:

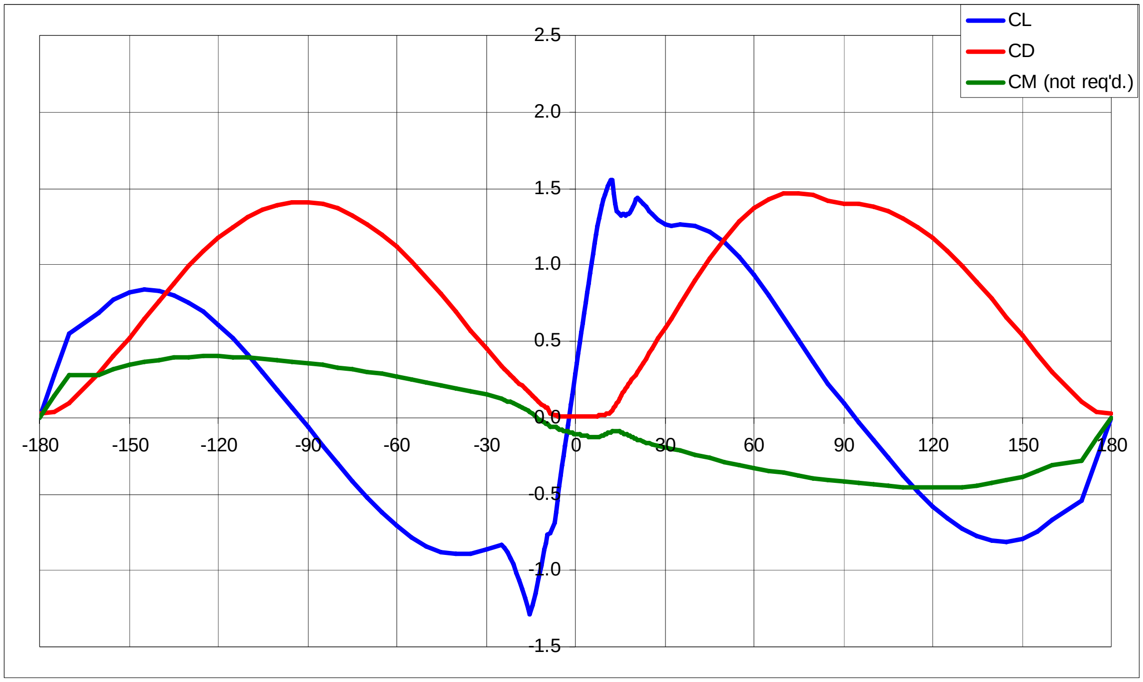
3D Corrected Coefficients of the DU40 Airfoil



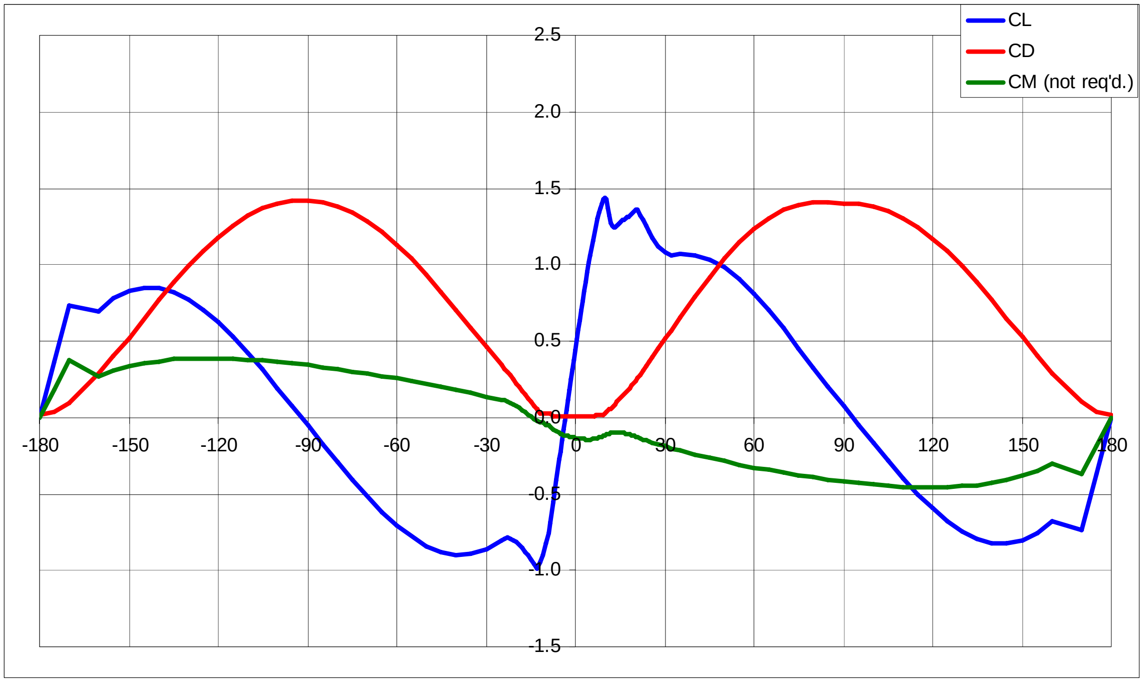
3D Corrected Coefficients of the DU35 Airfoil



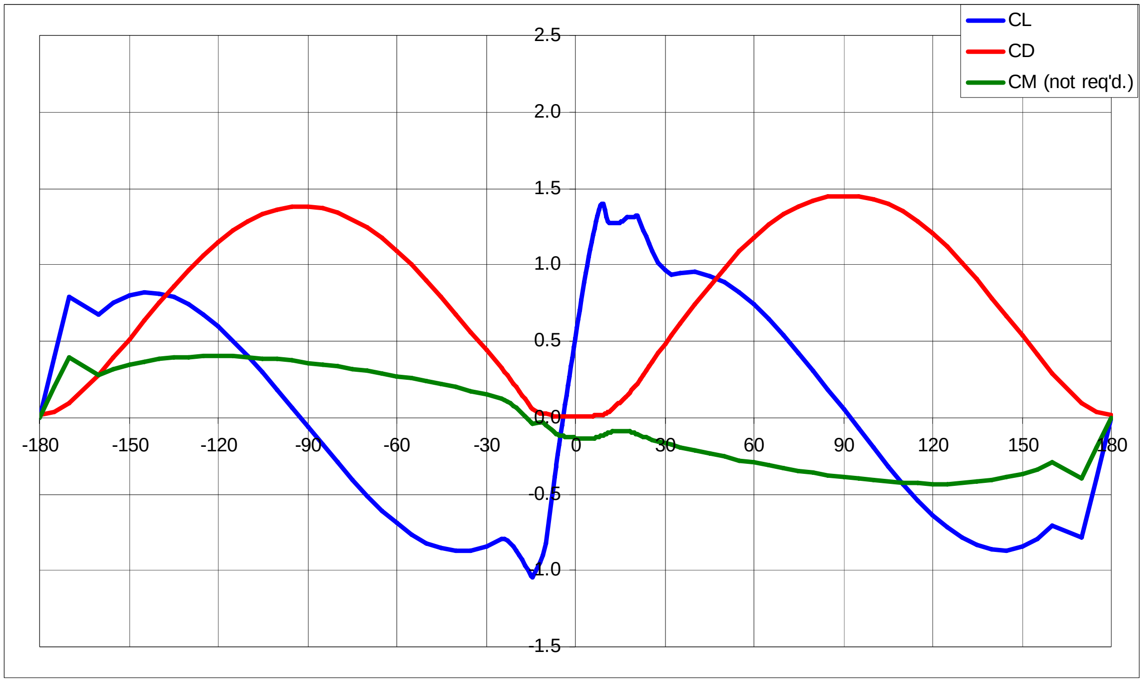
3D Corrected Coefficients of the DU30 Airfoil



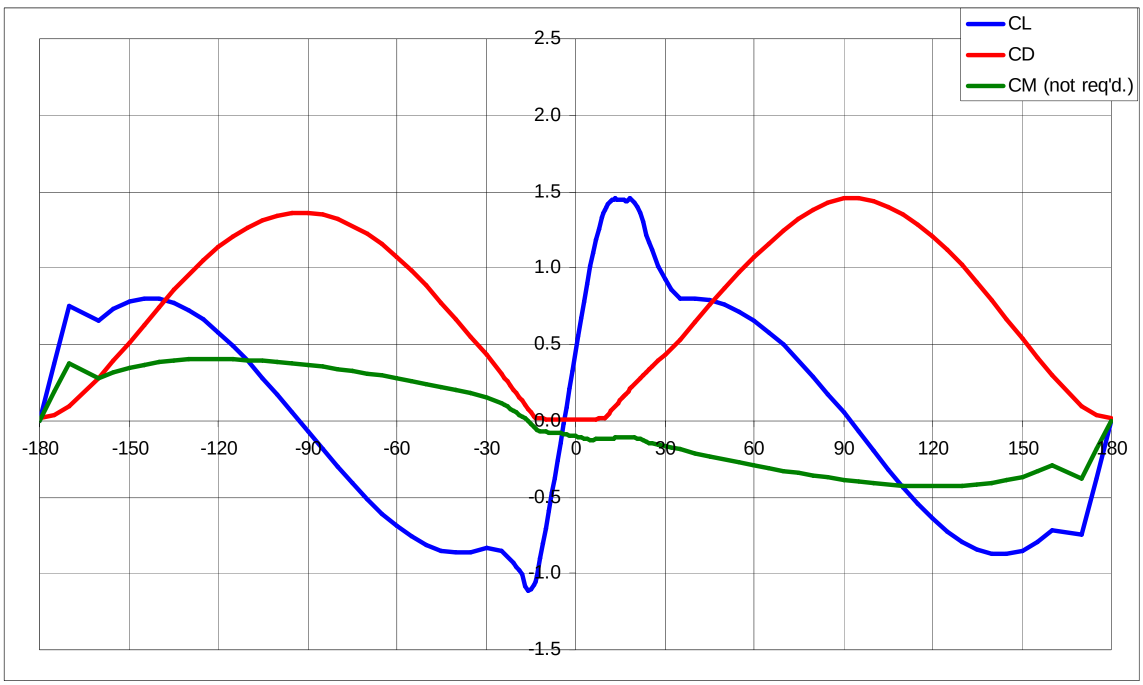
3D Corrected Coefficients of the DU25 Airfoil



3D Corrected Coefficients of the DU21 Airfoil



3D Corrected Coefficients of the NACA64 Airfoil



Nacelle and Hub Properties:

As mentioned earlier, the hub is located 5m upwind of the tower centerline at 90m elevation above the MSL when the tower is undeflected. The NREL 5MW baseline model uses the same vertical distance from the tower-top to the hub height used by the DOWEC study—that is, 2.4m from Table 6 on page 26 of Ref. 6. The elevation of the yaw bearing is consequently 87.6m. With a shaft tilt of 5˚, this makes the distance directed along the shaft from the hub center to the yaw axis 5.01910m and the vertical distance along the yaw axis from the tower-top to the shaft 1.96256m. The distance directed along the shaft from the hub center to the main bearing is taken to be 1.912m, from Table 6 on page 26 of Ref. 6.

The hub mass is taken to be 56,780 kg like the REpower 5M and is located at the hub center. The hub inertia about the shaft is taken to be 115,926 kgm^2. This was found by assuming that the hub spindel is a thin spherical shell with a radius 0.25m longer than the hub radius (due to the fact that the pitch bearing is located within the spindel—0.25m is chosen since the nacelle height of the DOWEC 6MW is 3.5m based on Table 6 on page 26 of Ref. 6), which have theoretical mass moment of inertias of: Ixx = 2/3*m*r^2.

The nacelle mass is taken to be 240,000 kg like the REpower 5M and is located 1.9m downwind of the yaw axis like the DOWEC 6MW (from Table 7 on page 27 of Ref. 6) and 1.75m above the yaw bearing, which is half the height of the DOWEC 6MW nacelle (from Table 6 on page 26 of Ref. 6). The nacelle inertia about the yaw axis is taken to be 2,607.89E3 kgm^2. This was chosen to be the same as the DOWEC 6MW's nacelle inertia about its nacelle c.g. and translated to the yaw axis using the parallel axis theorem with the nacelle mass and downwind distance to the nacelle c.g..

The nacelle yaw actuator is taken to have a natural frequency of 3Hz, which is equivalent to the highest full structural system natural frequency in the FAST model, and a damping ratio of 2% critical. This resulted in an equivalent nacelle yaw linear spring constant of 9,028.32E6 N-m/rad and an equivalent nacelle yaw linear damping constant of 19.16E6 N-m/rad/s.

The nacelle and hub properties discussed in this section are summarized in the table below:

Nacelle and Hub Properties

Elevation of Yaw Bearing Above MSL	87.6	m
Vertical Distance Along Yaw Axis from Yaw Bearing to Shaft	1.96256	m
Distance Along Shaft from Hub Center to Yaw Axis	5.01910	m
Distance Along Shaft from Hub Center to Main Bearing	1.912	m
Hub Mass	56,780	kg
Hub Inertia About Shaft Axis	115,926	kg-m^2
Nacelle Mass	240,000	kg
Nacelle Inertia About Yaw Axis	2,607,890	kg-m^2
Nacelle c.g. Location Downwind of Yaw Axis	1.9	m
Nacelle c.g. Location Above of Yaw Bearing	1.75	m
Equivalent Nacelle Yaw Linear Spring Constant	9,028,320,000	N-m/rad
Equivalent Nacelle Yaw Linear Damping Constant	19,160,000	N-m/rad/s

Drivetrain Properties:

The NREL 5MW baseline wind turbine model uses the same rated rotor speed (12.1 rpm), rated generator speed (1173.7 rpm), and gearbox ratio (97:1) as the REpower 5M machine. The gearbox is assumed to have no frictional losses—a requirement of the FAST-to-ADAMS preprocessor. The electrical efficiency of the generator is taken to be 94.4%. This is chosen to be roughly the same as the total mechanical to electrical conversion loss used by the DOWEC 6MW at rated—i.e., 3.5E5 Watts of power loss occur at about 6.25E6 Watts of aerodynamic power from Figure 15, page 24 of Ref. 6. The generator inertia about the high-speed shaft is taken to be 534.116 kgm^2, which is the same equivalent low-speed shaft generator inertia used in the DOWEC study—i.e., 5025500 kgm^2 from page 36 of Ref. 6.

The drive shaft is taken to have the same natural frequency as the RECOFF model and 5% critical damping ratio for the free-free mode with a rigid generator and rigid rotor. This resulted in an equivalent drive shaft linear spring constant of 867.637E6 N-m/rad and a damping constant of 6.215E6 N-m/rad/s.

The high-speed shaft brake is taken to have the same maximum brake torque to maximum generator torque ratio and the same time lag as used in the DOWEC study (from page 29 of Ref. 6). This resulted in a fully-deployed high-speed shaft brake torque of 28,116.2 N-m and a time lag of 0.6 seconds. This time lag is the amount of time it takes for the brake to fully engage once deployed. FAST and ADAMS use a simple linear ramp from 0 to full over the 0.6 seconds.

The drivetrain properties discussed in this section are summarized in the table below:

Drivetrain Properties

Rated Rotor Speed	12.1	rpm
Rated Generator Speed	1173.7	rpm
Gearbox Ratio	97	:1
Electrical Generator Efficiency	94.4	%
Generator Inertia About High-Speed Shaft	534.116	kg-m^2
Equivalent Drive Shaft Torsional Spring Constant	867,637,000	N-m/rad
Equivalent Drive Shaft Torsional Damping Constant	6,215,000	N-m/rad/s
Fully-Deployed High-Speed Shaft Brake Torque	28,116.2	N-m
High-Speed Shaft Brake Time Constant	0.6	sec

Support Structure Properties:

The properties of the support structure depend on whether the turbine will be installed in shallow water or deep water. The two different support structures are described in separate sections below.

Shallow Water:

The distributed tower properties of the NREL 5MW baseline model are based on the base diameter (6m) and thickness (0.027m), top diameter (3.87m) and thickness (0.019m), and effective mechanical steel properties of the tower used in the DOWEC study, as given in Table 9 on page 31 of Ref. 6. The radius and thickness of the tower are assumed to be linearly tapered from base to top. The tower is connected to a monopile with a constant diameter of 6m and a constant thickness of 0.060m. The tower base begins at an elevation of 10m above the MSL.

The monopile extends from here down to the mudline, which is at 20m below MSL. The Young's modulus is taken to be 210*10^9 Pa, the shear modulus is taken to be 80.8*10^9 Pa and the effective density of the steel is taken to be 8500 kg/m^3. The 8500 kg/m^3 is meant to be an increase above steel's typical value of 7850 kg/m^3 in order to account for paint, bolts, welds, and flanges that are not accounted for in the thickness data. The resulting distributed tower properties are given in the table below:

Distributed Tower Properties

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (Nm^2)	TwSSStif (Nm^2)	TwGJStif (Nm^2)	TwEAStif (N)	TwFAIner (kg m)	TwSSIner (kg m)	TwFAcgOf (m)	TwSScgOf (m)
-20.00	0.00000	9517.14	1037.13E+9	1037.13E+9	798.098E+9	235.129E+9	41979.2	41979.2	0.0	0.0
10.00	0.27881	9517.14	1037.13E+9	1037.13E+9	798.098E+9	235.129E+9	41979.2	41979.2	0.0	0.0
10.00	0.27882	4306.51	474.49E+9	474.49E+9	365.133E+9	106.396E+9	19205.6	19205.6	0.0	0.0
17.76	0.35094	4030.44	413.08E+9	413.08E+9	317.878E+9	99.576E+9	16720.0	16720.0	0.0	0.0
25.52	0.42306	3763.45	357.83E+9	357.83E+9	275.356E+9	92.979E+9	14483.4	14483.4	0.0	0.0
33.28	0.49517	3505.52	308.30E+9	308.30E+9	237.242E+9	86.607E+9	12478.7	12478.7	0.0	0.0
41.04	0.56729	3256.66	264.08E+9	264.08E+9	203.220E+9	80.459E+9	10689.2	10689.2	0.0	0.0
48.80	0.63941	3016.86	224.80E+9	224.80E+9	172.987E+9	74.534E+9	9098.9	9098.9	0.0	0.0
56.56	0.71153	2786.13	190.06E+9	190.06E+9	146.252E+9	68.834E+9	7692.7	7692.7	0.0	0.0
64.32	0.78365	2564.46	159.49E+9	159.49E+9	122.735E+9	63.357E+9	6455.7	6455.7	0.0	0.0
72.08	0.85576	2351.87	132.77E+9	132.77E+9	102.167E+9	58.105E+9	5373.9	5373.9	0.0	0.0
79.84	0.92788	2148.34	109.54E+9	109.54E+9	84.291E+9	53.077E+9	4433.6	4433.6	0.0	0.0
87.60	1.00000	1953.87	89.49E+9	89.49E+9	68.863E+9	48.272E+9	3622.1	3622.1	0.0	0.0

The entries in the first column, Elevation, are the vertical locations along the tower centerline relative to the MSL. HtFract is the fractional height along the tower centerline from the mudline (0.0) to the tower top (1.0). The rest of columns are similar to those described for the distributed blade properties.

The resulting overall (integrated) tower + monopile mass is 522,617 kg and is centered at 37.172m along the tower centerline above the mudline. This result follows directly from the overall tower height of 87.6m.

The NREL 5MW baseline model incorporates 1% critical structural damping in all modes of the isolated tower (without the top mass present), which corresponds to the values used in the DOWEC study from page 21 of Ref. 6.

The table below summarizes the undistributed tower properties discussed in this section:

Undistributed Tower Properties

Tower-Top Height Above MSL	87.6 m
Tower-Base Height Above MSL	10 m
Water Depth (From MSL)	20 m
Overall (Integrated) Mass	522,617 kg
c.g. Location (w.r.t. Mudline Along Tower Centerline)	37.172 m
Structural Damping Ratio (All Modes)	1 %

Deep Water:

The distributed tower properties of the NREL 5MW baseline model are based on the base diameter (6m) and thickness (0.027m), top diameter (3.87m) and thickness (0.019m), and effective mechanical steel properties of the tower used in the DOWEC study, as given in Table 9 on page 31 of Ref. 6. The Young's modulus is taken to be 210*10^9 Pa, the shear modulus is taken to be 80.8*10^9 Pa and the effective density of the steel is taken to be 8500 kg/m^3. The 8500 kg/m^3 is meant to be an increase above steel's typical value of 7850 kg/m^3 in order to account for paint, bolts, welds, and flanges that are not accounted for in the tower thickness data. The radius and thickness of the tower are assumed to be linearly tapered from base to top. The thickness of the tower was scaled up relative to the values indicated above in order to strengthen the tower since the REpower 5M machine has a larger tower-top mass than the DOWEC 6MW machine. An increase of 30% was chosen to ensure that the first tower fore-aft (FA) and side-to-side (SS) tower frequencies lie between 1P and 3P through the operational range of the wind turbine in a Campbell diagram. The resulting distributed tower properties are given in the table below:

Distributed Tower Properties

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (Nm^2)	TwSSStif (Nm^2)	TwGJStif (Nm^2)	TwEAStif (N)	TwFAIner (kg m)	TwSSIner (kg m)	TwFAcgOf (m)	TwSScgOf (m)
0.00	0.0	5590.87	614.34E+9	614.34E+9	472.75E+9	138.13E+9	24866.3	24866.3	0.0	0.0
8.76	0.1	5232.43	534.82E+9	534.82E+9	411.56E+9	129.27E+9	21647.5	21647.5	0.0	0.0
17.52	0.2	4885.76	463.27E+9	463.27E+9	356.50E+9	120.71E+9	18751.3	18751.3	0.0	0.0
26.28	0.3	4550.87	399.13E+9	399.13E+9	307.14E+9	112.43E+9	16155.3	16155.3	0.0	0.0
35.04	0.4	4227.75	341.88E+9	341.88E+9	263.09E+9	104.45E+9	13838.1	13838.1	0.0	0.0
43.80	0.5	3916.41	291.01E+9	291.01E+9	223.94E+9	96.76E+9	11779.0	11779.0	0.0	0.0
52.56	0.6	3616.83	246.03E+9	246.03E+9	189.32E+9	89.36E+9	9958.2	9958.2	0.0	0.0
61.32	0.7	3329.03	206.46E+9	206.46E+9	158.87E+9	82.25E+9	8356.6	8356.6	0.0	0.0
70.08	0.8	3053.01	171.85E+9	171.85E+9	132.24E+9	75.43E+9	6955.9	6955.9	0.0	0.0
78.84	0.9	2788.75	141.78E+9	141.78E+9	109.10E+9	68.90E+9	5738.6	5738.6	0.0	0.0
87.60	1.0	2536.27	115.82E+9	115.82E+9	89.13E+9	62.66E+9	4688.0	4688.0	0.0	0.0

The entries in the first column, Elevation, are the vertical locations along the tower centerline relative to the ground or MSL. HtFract is the fractional height along the tower centerline from the tower base (0.0) to the tower top (1.0). The rest of columns are similar to those described for the distributed blade properties.

The resulting overall (integrated) tower mass is 347,460 kg and is centered at 38.234m along the tower centerline above the MSL. This result follows directly from the overall tower height of 87.6m.

The NREL 5MW baseline model incorporates 1% critical structural damping in all modes of the isolated tower (without the top mass present), which corresponds to the values used in the DOWEC study from page 21 of Ref. 6.

The table below summarizes the undistributed tower properties discussed in this section:

Undistributed Tower Properties

Height Above MSL	87.6 m
Overall (Integrated) Mass	347,460 kg
c.g. Location (w.r.t. MSL Along Tower Centerline)	38.234 m
Structural Damping Ratio (All Modes)	1 %

Overall Body Mass Matrix of Rigid Turbine:

In the preliminary stages of offshore platform design, it is convenient to use frequency-domain analysis techniques. Such techniques generally consider only the six rigid body modes of the platform (surge, sway, heave, roll, pitch, and yaw) and ignore the flexibility of the system (platform and wind turbine). Knowledge of the 6x6 body mass matrix of the 5MW baseline wind turbine is required for such analyses. As defined in equation 141 on page 149 of Ref. 15, the body mass matrix of the rigid, undeflected 5MW baseline wind turbine in deep water to four-significant digits is:

$$M_{ij} = \begin{bmatrix} 697{,}500 & 0 & 0 & 0 & 44{,}630{,}000 & 0 \\ 0 & 697{,}500 & 0 & -44{,}630{,}000 & 0 & -144{,}800 \\ 0 & 0 & 697{,}500 & 0 & 144{,}800 & 0 \\ 0 & -44{,}630{,}000 & 0 & 3{,}566{,}000{,}000 & 0 & 11{,}670{,}000 \\ 44{,}630{,}000 & 0 & 144{,}800 & 0 & 3{,}551{,}000{,}000 & 0 \\ 0 & -144{,}800 & 0 & 11{,}670{,}000 & 0 & 25{,}410{,}000 \end{bmatrix}$$

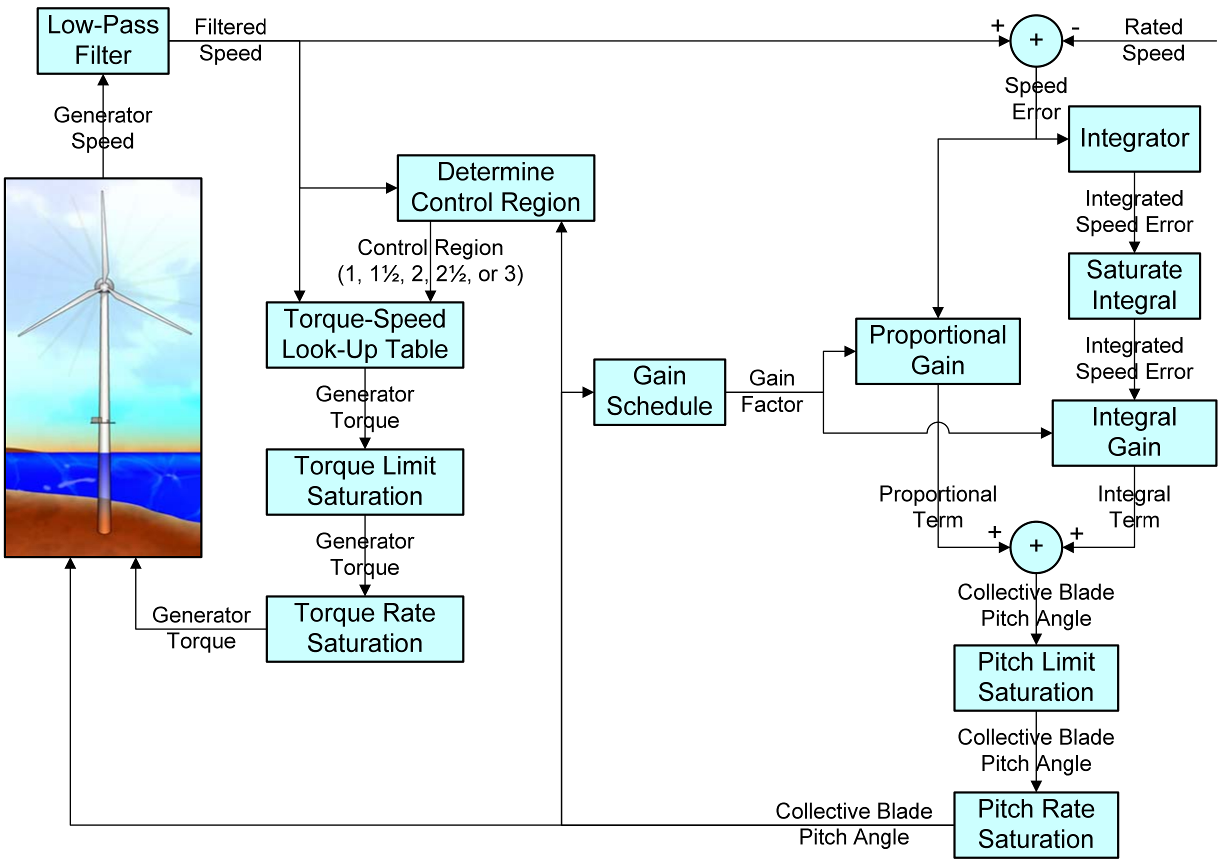
This matrix was derived by linearizing the FAST model about a reference point located at the tower centerline at the base of the tower (i.e., MSL). The row/column order is: 1 = surge, 2 = sway, 3 = heave, 4 = roll, 5 = pitch, 6 = yaw and the units in the matrix are: kg, kg-m, and kg-m^2.

Naturally, since FAST does not have a tower torsion DOF, neither does it have knowledge of the yaw inertia of the tower about the tower centerline. So, the effects of the tower yaw inertia are not included in the body mass matrix given above. By integration of the distributed tower inertia data along the length of the tower, this yaw inertia is estimated to be 2,241,820 kg-m^2. This inertia could be added to element (6,6) of the body mass matrix given above, but it is not straightforward how this additional inertia will affect the other elements in the matrix. However, neglecting the tower yaw inertia from the body mass matrix should not be of significant concern, since it may be seen that the addition of the tower yaw inertia to element (6,6) will only increase the overall turbine yaw inertia (tower, nacelle, and rotor) by a small amount (less than 10%). User's of the body mass matrix should be aware of this issue and address it as they see fit.

Variable-Speed Generator Torque and Blade Pitch Control Properties:

The NREL 5MW baseline wind turbine incorporates a control system that consists of a variable-speed generator torque controller and a full-span collective blade pitch controller. Both controllers use the generator speed measurement as the sole input. The goal of the controller is to maximize power capture below, and regulate speed above, the rated operating point. The control system is implemented as an external dynamic-link-library (DLL) in the style of Garrad Hassan's *BLADED* wind turbine software package. The control system does not attempt to regulate the nacelle yaw angle nor does it attempt to control the deployment of the high speed shaft brake. A flowchart of the control system calculations is given in the following figure.

Control System Flowchart

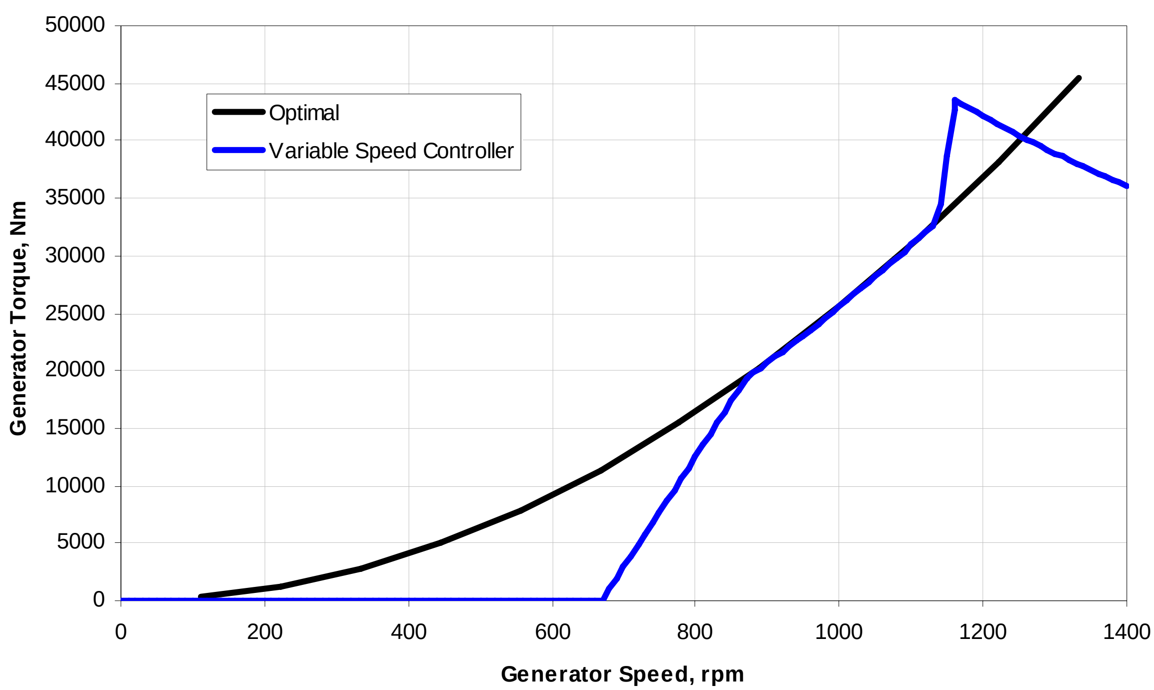


The generator speed measurement for both the torque and pitch controllers is filtered using a recursive, single-pole, low-pass filter with exponential smoothing. The corner frequency (-3dB point) of the low pass filter is set to 0.25 Hz, which is chosen to be roughly ¼ of the blade edgewise natural frequency.

The generator torque is computed as a function of the filtered generator speed using a variable-speed controller. The variable-speed controller incorporates five control regions: 1, 1½, 2, 2½, and 3. Region 1 is the control region before cut-in where the generator torque is zero so that no power is extracted from the wind; instead, the wind is used to accelerate the rotor. Region 2 is the control region for optimizing power capture. Here, the generator torque is proportional to the square of the filtered generator speed. In region 3, the generator power is held constant so that the generator torque is inversely proportional to the filtered generator speed. Region 1½ is the start-up region and is a linear transition between regions 1 and 2. It is used to place a lower limit on the generator speed in order to limit the operational speed range. Region 2½ is a linear transition between regions 2 and 3 with a torque slope corresponding to the slope of an induction machine. Region 2½ is typically needed (as is the case for this 5MW model) since a machine does not typically reach rated torque at its rated speed using Region 2's control law [i.e., the optimal K is typically lower than that which would make the rated torque = K*(rated speed)^2, since the rated speed is generally limited from optimal in order to limit tip speed for noise reasons].

The peak of the power coefficient as a function of tip-speed ratio and blade pitch surface was found by running FAST simulations at a number of fixed rotor speeds and a number of fixed rotor-collective blade pitch angles at a fixed wind speed of 8 m/s. From these simulations, the peak power coefficient of 0.482 was found to occur at a tip-speed ratio of 7.55 and a rotor-collective blade pitch of 0.0˚. With the 97:1 gearbox ratio, this resulted in an optimal constant of proportionality of 0.0255764 N-m/rpm^2 in the region 2 control law. With the rated generator speed of 1173.7 rpm, rated electric power of 5MW, and a generator efficiency of 94.4%, the rated mechanical power is 5.296610MW and the rated generator torque is 43,093.55 N-m. Region 1½ spans the range of generator speeds between 670 rpm and 30% above this value, or 871 rpm. The minimum generator speed of 670 rpm corresponds to the minimum rotor speed of 6.9 rpm used by the REpower 5M machine[16]. The transitional generator speed between Regions 2½ and 3 is taken to be 99% of the rated generator speed, or 1,161.963 rpm. The generator slip percentage in region 2½ is taken to be 10% in accordance with the value used in the DOWEC study—reference page 24 of Ref. 6. The resulting generator torque versus generator speed curve is shown in the figure below:

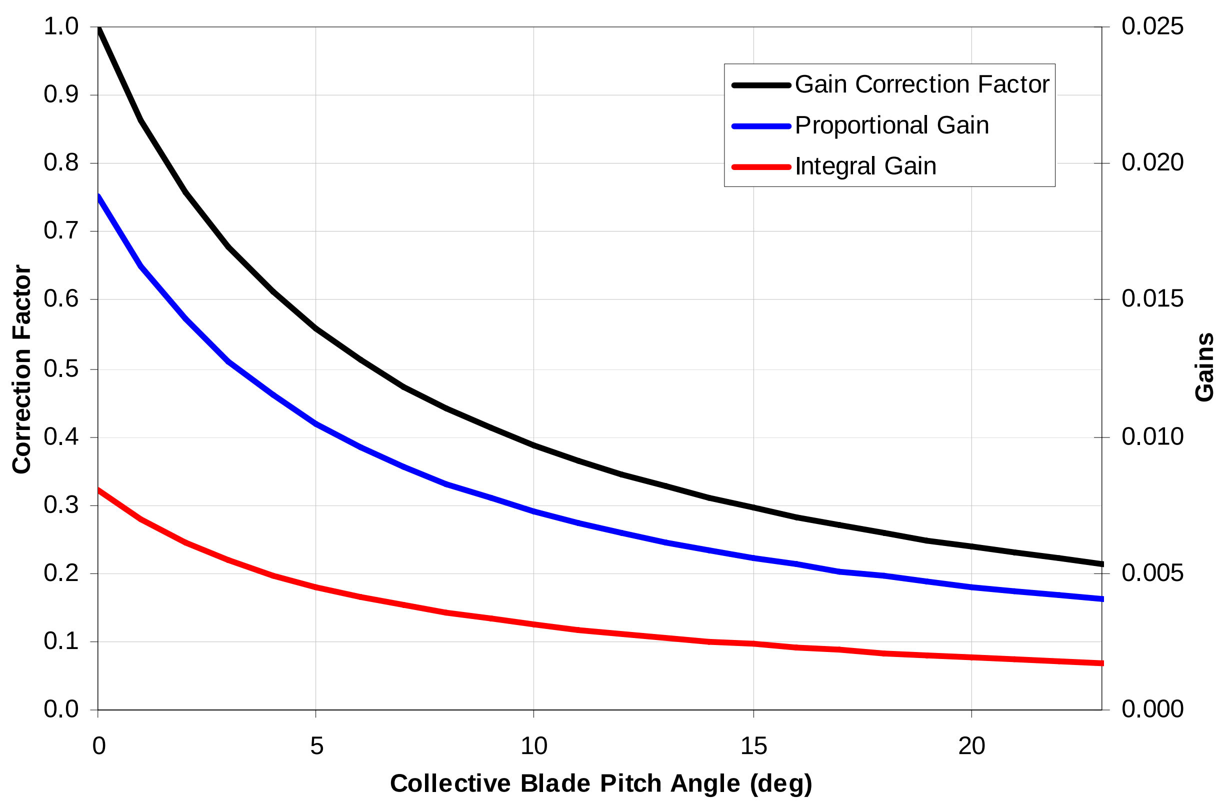
Variable-Speed Control System Torque versus Speed Curve



Finally, a conditional statement is placed on the variable speed controller so that the torque is computed as if it was in Region 3 regardless of the generator speed whenever the previous pitch angle command is greater or equal to 1˚. This results in improved output power quality (fewer dips below rated) at the expense of short term overloading of the generator and gearbox. To avoid excessive overloading of both, the torque is saturated to a maximum of 10% above rated, or 47,402.91 N-m. Also, a torque rate limit of 15,000 N-m/s is imposed.

The full-span collective blade pitch angle commands are computed using gain-scheduled PI control on the speed error between the filtered generator speed and the rated generator speed (1173.7 rpm). The parameter for determining the gain scheduling correction factor is the previous pitch angle command. The gains (see the figure below) were derived according to the technique documented in Ref. 4. In particular, the partial derivative of the rotor power with respect to the collective pitch angle as a function of the pitch angle was computed by performing a linearization analysis in FAST at a number of fixed pitch angles. The frozen wake assumption was used when computing these partial derivatives through a minor modification to AeroDyn.

Pitch Control System Gain-Scheduling Law



The pitch rate limit is set at 8˚/sec in absolute value. This is speculated to be the pitch rate limit of conventional 5MW machines based on GE Wind's long blade test program. The minimum and maximum pitch settings are chosen to be 0˚ and 90˚, respectively. The integral term in the PI controller is saturated between these limits so as to ensure fast response between the Region 2 / Region 3 transition.

Due to limitations in the code, the FAST model does not include any pitch actuator dynamic effects. However, pitch actuator dynamics are required in ADAMS. Hence, in the ADAMS model, the blade pitch actuator is taken to have a very high natural frequency of 30Hz, which is equivalent to 10x the highest full structural system natural frequency in the FAST model, and a damping ratio of 2% critical. This resulted in an equivalent blade pitch linear spring constant of 971.350E6 N-m/rad and an equivalent blade pitch linear damping constant of 0.206E6 N-m/rad/s.

The variable-speed generator-torque and blade pitch control properties discussed in this section are summarized in the table below:

Variable-Speed Generator-Torque and Blade Pitch Control Properties

Corner Frequency of Generator Speed Low Pass Filter	0.25 Hz
Peak Power Coefficient	0.482
Tip Speed Ratio at Peak Power Coefficient	7.55
Rotor Collective Blade Pitch Angle at Peak Power Coefficient	0.0 º
Generator Torque Constant in Region 2	0.0255764 N-m/rpm^2
Rated Mechanical Power	5.296610 MW
Rated Generator Torque	43,093.55 N-m
Transitional Generator Speed Between Regions 1 and 1 1/2	670 rpm
Transitional Generator Speed Between Regions 1 1/2 and 2	871 rpm
Transitional Generator Speed Between Regions 2 1/2 and 3	1,161.963 rpm
Generator Slip Percentage in Region 2 1/2	10 %
Minimum Pitch For Ensuring Region 3 Torque	1 º
Maximum Generator Torque	47,402.91 N-m
Maximum Generator Torque Rate	15,000 N-m/s
Proportional Gain at Minimum Pitch Setting	0.01882681 sec
Integral Gain at Minimum Pitch Setting	0.008068634
Pitch Angle at Which Rotor Power Has Doubled	6.302336 º
Minimum Pitch Setting	0 º
Maximum Pitch Setting	90 º
Maximum Absolute Pitch Rate	8 º/sec
Equivalent Blade Pitch Linear Spring Constant	971,350,000 N-m/rad
Equivalent Blade Pitch Linear Damping Constant	206,000 N-m/rad/s

Degrees-of-Freedom and Timesteps:

Not including platform motion, the FAST model incorporates 16 degrees-of-freedom (DOFs) as follows:

- 2 flap and 1 edge mode DOFs for each of the 3 blades
- 1 variable-speed generator DOF and 1 driveshaft torsional DOF
- 1 nacelle yaw actuator DOF
- 2 fore-aft and 2 side-to-side mode DOFs in the tower

The ADAMS model incorporates 378 DOFs as follows:

- 102 DOFs, including flap and edge shear and bending, torsion, and extension DOFs, in each of the 3 blades
- 1 pitch actuator DOF in each of the 3 blades
- 1 variable-speed generator DOF and 1 driveshaft torsional DOF
- 1 nacelle yaw actuator DOF

- 66 DOFs, including fore-aft and side-to-side shear and bending, torsion, and extension DOFs, in the tower

Time integration occurs at a constant time step of 0.0125 seconds in FAST's fixed-step size integration scheme and at a maximum step size of 0.0125 seconds in ADAMS' variable-step size integration scheme. Aerodynamic calculations are performed every other time step (0.025 seconds) to ensure that there are at least 200 azimuth step computations per revolution. These time steps are the largest possible to ensure numerical stability across a range of operating modes.

Full-System Natural Frequencies:
In order to provide a cursory view of the structural response of the full system, NREL performed an eigenanalysis on the stationary turbine (not spinning) in the deepwater configuration in order to obtain full system natural frequencies. The eigenanalysis ignores gravitational and aerodynamic loads, as well as structural damping. Results for the first 13 full system natural frequencies are listed in the table below. In FAST, these are obtained by performing an eigenanalysis in MATLAB® on the first order state matrix created from a FAST linearization analysis. In ADAMS, the frequencies are obtained by invoking a "LINEAR/EIGENSOL" command, which linearizes the complete ADAMS model and computes eigendata. The ADAMS results were obtained without mass offsets in the blade in order to ensure consistency between the FAST and ADAMS models. The agreement between FAST and ADAMS is quite good.

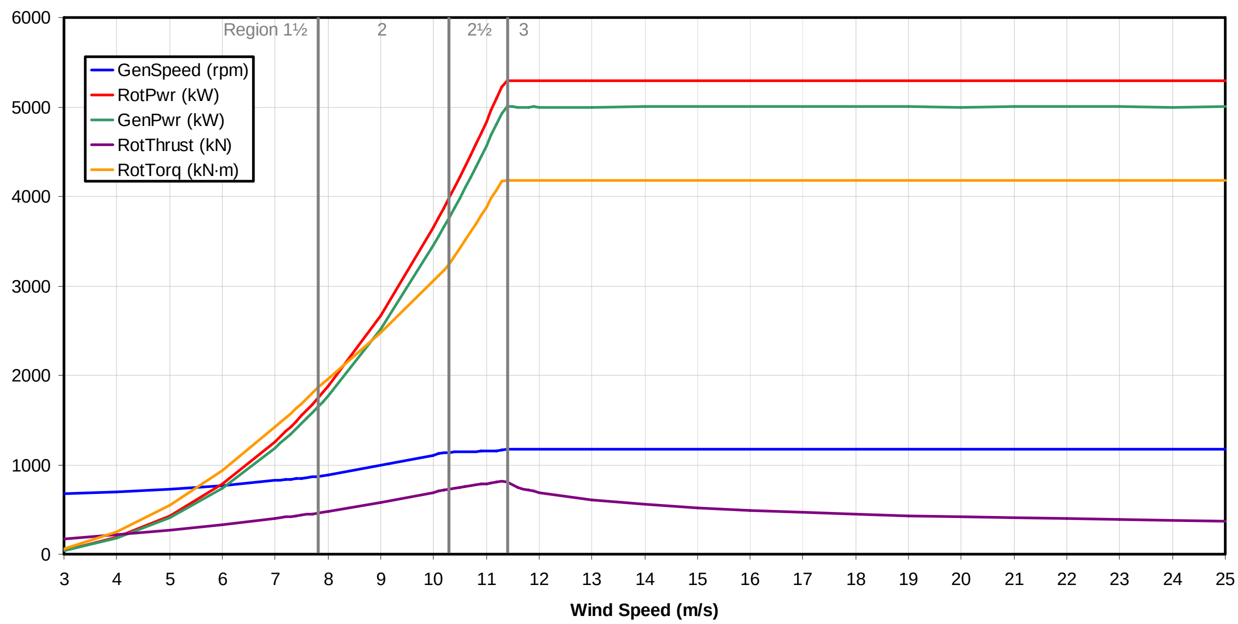
Full System Natural Frequencies at 0 RPM, Hz

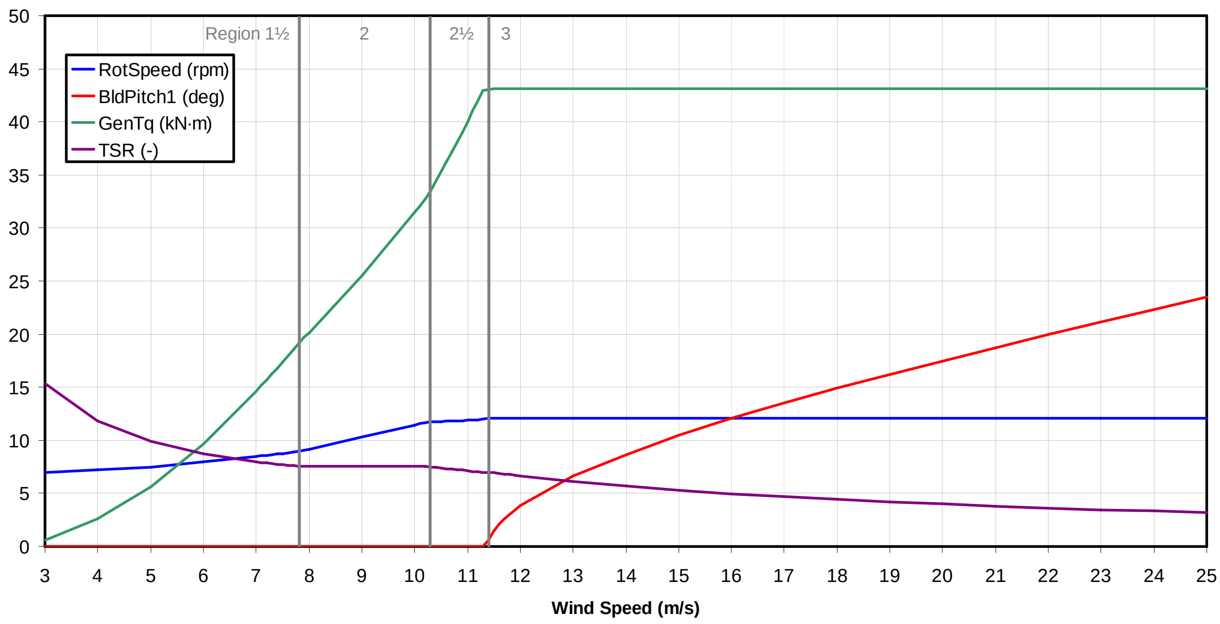
Mode	Description	FAST	ADAMS
1	1st Tower SS	0.31780	0.31620
2	1st Tower FA	0.31994	0.31930
3	1st Drivetrain	0.62149	0.61100
4	1st Blade Asym. Flapwise Yaw	0.67250	0.63840
5	1st Blade Asym. Flapwise Pitch	0.67084	0.66900
6	1st Blade Collective Flap	0.70130	0.70230
7	1st Blade Asym. Edgewise Pitch	1.07770	1.07510
8	1st Blade Asym. Edgewise Yaw	1.09270	1.08860
9	2nd Blade Asym. Flapwise Yaw	1.99320	1.70440
10	2nd Blade Asym. Flapwise Pitch	1.93830	1.85760
11	2nd Blade Collective Flap	2.01980	1.96180
12	2nd Tower SS	2.94270	2.93910
13	2nd Tower FA	2.91650	2.84620

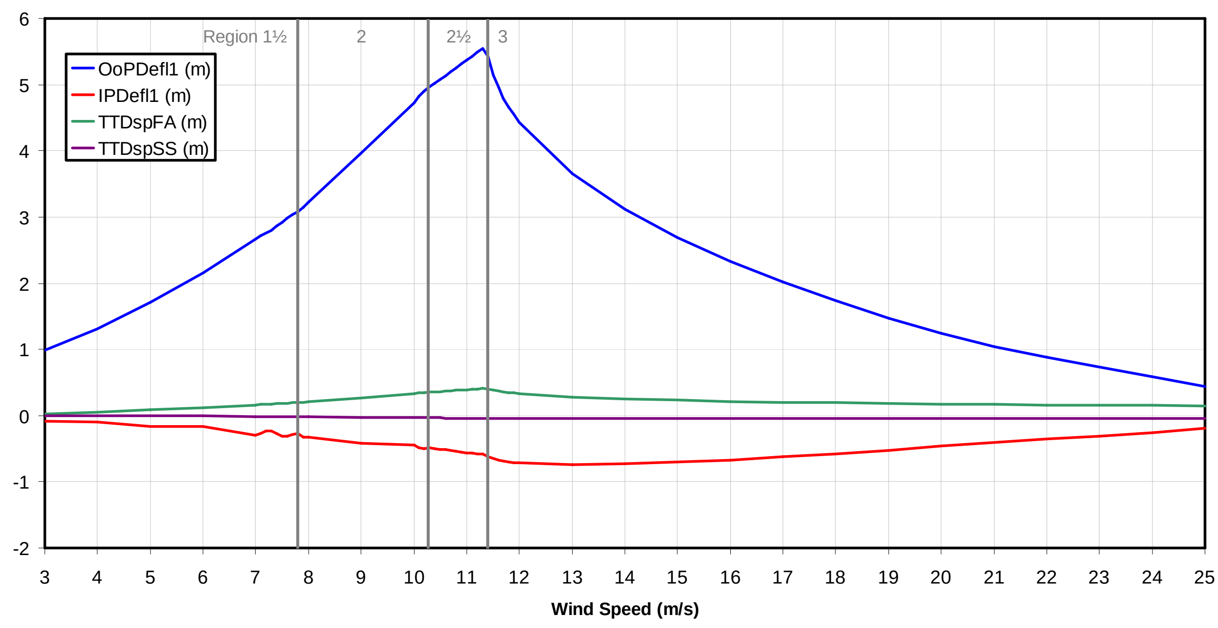
Wind Speed Relationships and Initial Conditions:
The figures below contain many basic machine specifications as a function of wind speed, such as rotor/generator speed, torque, thrust, pitch, etc. These were obtained by running a number of FAST simulations at many fixed wind speeds. The simulations were run using the EQUILibrium wake option of AeroDyn with all DOFs enabled. These relationships can be used, for example, to set initial values of rotor speed and blade pitch in simulations.

Wind Speed Relationships Legend

BldPitch1	Pitch Angle of Blade 1
GenPwr	Electrical Generator Power
GenSpeed	Angular Speed of the High-Speed Shaft and Generator
GenTq	Electrical Generator Torque
IPDefl1	In-Plane Tip Deflection of Blade 1
OoPDefl1	Out-of-Plane Tip Deflection of Blade 1
RotPwr	Mechanical Rotor Power
RotSpeed	Angular Speed of the Low-Speed Shaft and Rotor
RotThrust	Rotor Thrust
RotTorq	Mechanical Rotor Torque
TSR	Rotor Blade Tip Speed Ratio
TTDspFA	Fore-Aft Displacement of the Tower Top and Yaw Bearing
TTDspSS	Side-to-Side Displacement of the Tower Top and Yaw Bearing







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